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Memory Effects in Electron Transport in Si Inversion Layers in the Dilute Regime: Individuality versus Universality

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In order to separate the universal and sample-specific effects in the conductivity of high-mobility Si inversion layers, we studied the electron transport in the same device after cooling it down to 4 K at different fixed values of the gate voltage $V^{\rm cool}$. Different $V^{\rm cool}$ did not modify significantly either the momentum relaxation rate or the strength of electron-electron interactions. However, the temperature dependences of the resistance and the magnetoresistance in parallel magnetic fields, measured in the vicinity of the metal-insulator transition in 2D, carry a strong imprint of individuality of the quenched disorder determined by $V^{\rm cool}$. This demonstrates that the observed transition between "metallic" and insulating regimes involves both universal effects of electron-electron interaction and sample-specific effects. Far away from the transition, at lower carrier densities and lower resistivities $\rho < 0.1h/e^2$, the transport and magnetotransport become nearly universal.

After almost a decade of intensive research, the apparent metal-insulator transition (MIT) in two-dimensional (2D) systems remains a rapidly evolving field [1]. The central problem in this field is whether the anomalous low-temperature behavior of the conductivity, observed in high-mobility structures in the dilute limit, signifies a novel quantum ground state in strongly-correlated systems, or this is a semiclassical effect of disorder on electron transport. Indeed, a great body of experimental data demonstrates that, at least at sufficiently large carrier densities (consequently, weak interactions), the low-temperature behavior of disordered systems is governed by the universal quantum corrections to the conductivity [2]. On the other hand, there are also observations that near the apparent 2D MIT, the behavior of dilute systems is very rich, and does not necessarily follow the same pattern (e. g., even for the same system, as Si MOSFETs, the "critical" resistance and the high-field magnetoresistance vary significantly for different samples [3,4]). This duality (universality versus individuality) is reflected in two approaches to the theoretical description of the "metallic" regime: some models, based on strong electron-electron interactions, treat the transition as a universal phenomenon [5–10], whereas the others emphasize the role of a sample-specific disorder (traps, localized spins, potential fluctuations, etc.) [11–15].

In order to find a definite experimental answer to this problem and to separate universal and non-universal ("individuality") effects in the vicinity of the 2D MIT, we have studied the electron transport in the same Si MOS structure, which was slowly cooled down from room temperature to T =4 K at different fixed values of the gate voltage $V_g = V^{\rm cool}$ [16]. Changing the cooling conditions allowed us to vary the confining potential and the density of quenched localized states without affecting the main parameters which control electron-electron interactions in the system of mobile electrons: the momentum relaxation rate and the interaction constants. By tuning V_g at low temperatures, we varied the electron density n over the range $n = (0.7 - 3) \times 10^{11}{\rm cm}^{-2}$ in a system with a snapshot disorder pattern. Two key features of the 2D MIT, strong dependences of the resistivity on the temperature and parallel magnetic field, have been studied.

We have observed two distinct regimes as a function of the electron density. At relatively high densities (resistivity $\rho \leq 0.1h/e^2$), the dependences $R(T)$ and $R(B_\parallel)$ in weak parallel magnetic fields $B_\parallel$ are similar for different cooldowns; the similarity indicates 'universal' behavior. In contrast, at low densities ($\rho \sim (0.1-1)h/e^2$), or in moderate and strong parallel fields $g\mu_B B_\parallel \sim E_F \gg k_B T$, the cooling conditions affect dramatically the electron transport. This observation provides direct experimental evidence that the behavior of dilute systems becomes sample-specific near the apparent 2D MIT no matter how one approaches the transition (either by decreasing the electron density, or by increasing the parallel magnetic field).

The resistivity measurements were performed on a high mobility Si-MOSFET sample [17] at the bath temperatures $0.05 - 1.2$ K. The crossed magnetic field system allowed to accurately align the magnetic field parallel to the plane of the 2DEG [18]. The carrier density, found from the period of Shubnikov-de Haas (SdH) oscillations, varies linearly with V_g: $n \approx C \times (V_g - V_{\rm th})$, where C ($= 1.103 \times 10^{11}$ /Vcm^2 for the studied sample) is determined by the oxide thickness. The 'threshold' voltage $V_{\rm th}$ varied little (within 0.15 V) for different cool-downs and remained fixed as long as the sample was maintained at low temperatures (up to a few months).

Figure 1 shows the mobility μ versus V_g for five different cool-downs with $V^{\rm cool} = 0, 5, 10, 18,$ and 25 V. The peak mobility for different cool-downs varies by less than $\sim 7\%$); this demonstrates that the momentum relaxation time τ is not strongly affected by the cooling conditions. We also observed that the amplitudes of the SdH oscillations are similar for different cool-downs, as shown in the inset to Fig. 1. These two observations are consistent with each other, since the quantum lifetime τ_q is nearly

equal to τ for Si-MOSFETs.

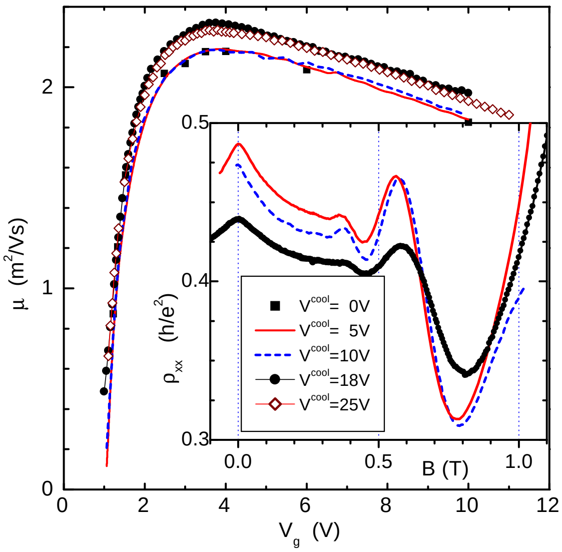

FIG. 1. The mobility versus the gate voltage for different cool-downs. The $V^{\rm cool}$ values for both the main panel and the inset are shown in the figure. Examples of the SdH oscillations, shown in the inset for the same $V_g = 1.15\,\mathrm{V}$, $T = 0.1\,\mathrm{K}$, $B_\parallel = 0.03\,\mathrm{T}$, demonstrate that the quantum time τ_q is not very sensitive to the cooling conditions. The carrier densities are (from top to bottom) $n = 1.081$, 1.092, 1.070 in units $10^{11}\mathrm{cm}^{-2}$.

Figure 2 a shows the dependences $\rho(T)$ for two cool-downs in the vicinity of the 2D MIT. Far from the transition, where $\rho \ll h/e^2$, the dependences $\rho(T)$ are cooldown-independent. However, in the vicinity of the transition ($\rho \sim h/e^2$), a dramatically different behavior is observed. The irreproducibility of $\rho(T)$ for different cool-downs is clearly seen for the curves in Fig. 2 which correspond to the same ρ at the lowest T: these curves, being different at higher temperatures, converge with decreasing T. The sample-specific memory effects vanish also at sufficiently low temperatures: this suggests that the underlying mechanism is related to the finite-temperature effects in a system which retains a quenched disorder. These results suggest that, in addition to universal effects, a finite-temperature and sample-specific mechanism, which strongly affects the resistivity, comes into play.

The 'critical' density n_c, which corresponds to the transition, was found from a linear extrapolation to zero of the density dependence of the activation energy $\Delta(n)$ in the insulating regime $\rho(T) \propto \exp(\Delta/T)$ [3,19]. The dependences $\rho(T)$, which corresponded to $n = n_c$ for two cool-downs shown in Fig. 2a, are highlighted in bold. It is clear that (i) the 'critical' densities and 'critical' resistivities depend on the cooling conditions, and (ii) the 'critical' dependences $\rho(T, n = n_c)$ are non-monotonic (see also Refs. [19,20]). Observation of the non-monotonic critical dependences $\rho_c(T)$ suggests that a) saturation of the temperature dependences at $n = n_c$, reported in [21], is not a universal effect, and b) the critical density is not necessarily associated with the sign change of $d\rho/dT(n)$ [19].

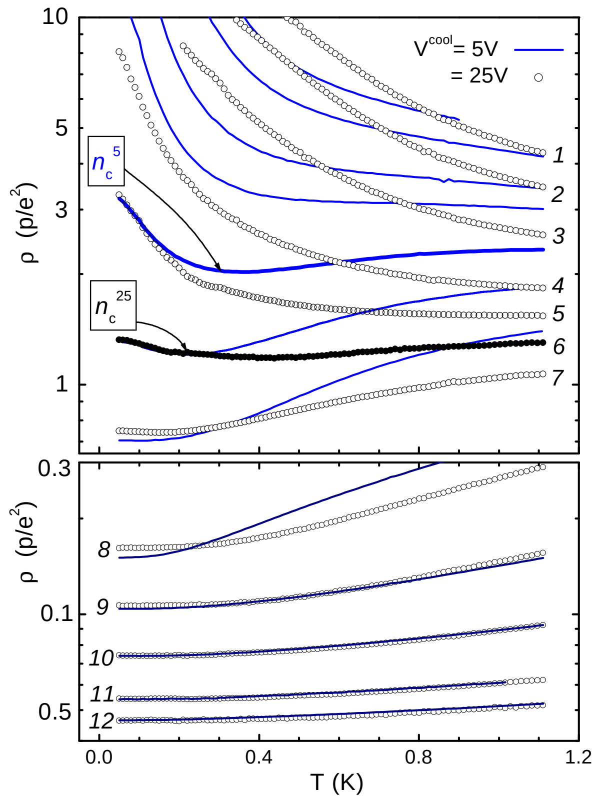

FIG. 2. Temperature dependences of the resistivity for two different cool-downs. The densities, which correspond to curves *1* to *12*, are as follow: 0.783, 0.827, 0.882, 0.942, 0.972, 1.001, 1.021, 1.31, 1.53, 1.87, 2.29, 2.58 in unites of $10^{11}\mathrm{cm}^{-2}$.

We now turn to the magnetoresistance (MR) in parallel fields; the data are shown in Figs. 3 and 4. This MR is usually associated with the spin effects [1,4]. In the theoretical models of the parallel-field MR, based on electron-electron interactions, the MR is controlled by the effective g^*-factor and the momentum relaxation time τ [5,10,22]. An important advantage of our method is that cooling of the same sample at different $V^{\rm cool}$ does not affect these parameters. Thus, one might expect to observe a sample-independent behavior if the MR is controlled solely by the universal interaction effects.

Firstly, let us consider the range of fields much weaker than the field of complete spin polarization ($g^*\mu_B B_\parallel \ll E_F$). The insets to Figs. 3 a and 3 b show that the MR is proportional to $B_\parallel^2$ at $g^*\mu_B B_\parallel/k_B T \le 1$. We found that the slope $d\rho/dB^2$ is nearly cooldown-independent (i.e. universal) only for the densities $n > 1.3 \times 10^{11}\mathrm{cm}^{-2}$ (which are by 30% greater than the critical density n_c),

or for the resistivities $\rho < 0.16h/e^2$ (compare insets to Figs. 3 a and 3 b). With approaching n_c, this universality vanishes: Figure 3 a shows that even when the zero-field resistivity is as small as $0.22h/e^2$, the slope varies by a factor of 1.3 for different $V^{\rm cool}$.

For the intermediate fields, $k_BT < g^*\mu_B B_\parallel < E_F$, the $\rho(B_\parallel)$ behavior is not universal over the whole density range $n = (1-3)\times 10^{11}$cm^{-2} (Figs. 3a,b). As n decreases and approaches n_c, the cooldown-dependent variations of $R(B_\parallel)$ increase progressively. Observation of large ($\sim 50\%$) non-universal variations of the MR at intermediate fields makes the scaling analysis [23] of the MR in this field range dubious.

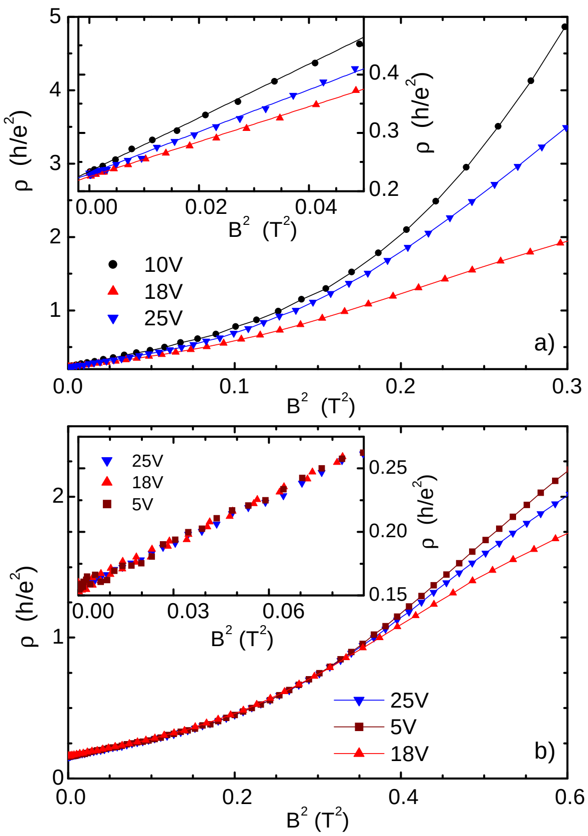

FIG. 3. Examples of the dependences $\rho(B_\parallel^2)$ at $T = 0.3$ K for the carrier density (a) 1.20×10^{11} cm^{-2} and (b) 1.34×10^{11} cm^{-2}. The insets blow up the low-field region of the quadratic behavior. The values of $V^{\rm cool}$ are indicated for each curve.

The influence of cooldown conditions becomes even more dramatic in strong fields, $B \gtrsim E_F/g^*\mu_B$. Despite the fact that the dependences $\mu(n)$ for different cool-downs are very similar (Fig. 1), we observed very large variations in the strong-field MR. Figures 4 a and 4 b show $R(B_\parallel)$ for different cool-downs at two values of n. The cooldown conditions cause factor-of-five changes in $\rho(B)$ in high fields and factor-of-two changes in the values of $B_\parallel = B_{\rm sat}$ at which the MR 'saturates' at a given carrier density. The latter quantity was determined from the intercept of the tangents at fields below and above MR saturation [4].

Figure 4 c shows the dependences $B_{\rm sat}(n)$ for different cool-downs. We also plotted here the density dependence of the field $B_{\rm pol} = 2E_F^*/g^*\mu_B = n\pi\hbar^2/m^*g^*\mu_B$, for the complete spin polarization of mobile electrons (m^* is the renormalized effective mass). The dependence $B_{\rm pol}(n)$ was calculated using sample-independent (universal) g^*m^* values [18]. Comparison between $B_{\rm sat}$ and $B_{\rm pol}$ shows that $B_{\rm sat}$ does not necessarily manifest the complete spin polarization, and that the coincidence of $B_{\rm sat}$ with $B_{\rm pol}$ reported in Ref. [24] may be rather accidental. This non-universal, sample-dependent behavior of B_{sat} agrees with earlier observations made on different samples [4]. We emphasize that the curves for different $V^{\rm cool}$ (in each of Figs. 4 a and b) correspond to the same density, as follows from Hall voltage and/or SdH oscillations measurements. The fact that $B_{\rm sat}$ is a cooldown-dependent parameter, suggests that the MR in strong parallel fields is not solely related to spin-polarization of mobile electrons; we speculate that it also reflects the spin polarization of the sample-specific localized electron states, which might have the effective g-factor quite different from that for the mobile electrons [4].

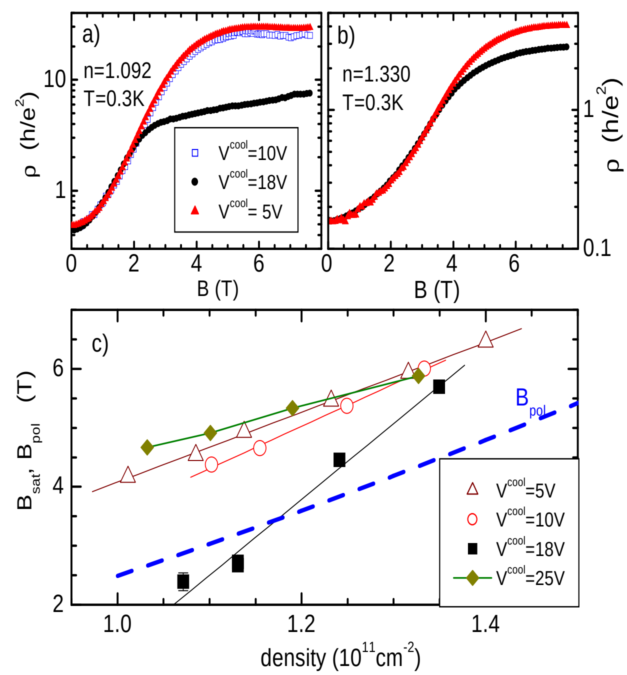

FIG. 4. Resistivity vs in-plane magnetic field for three cool-downs at two densities: a) $n = 1.092 \times 10^{11}$cm^{-2} and b) $n = 1.33 \times 10^{11}$cm^{-2}. c) The saturation field $B_{\rm sat}$ versus n for four different cool-downs. Solid lines are guides to the eye. Dashed line shows the field of complete spin polarization calculated on the basis of direct measurements of the spin susceptibility for mobile electrons [18].

It is worth mentioning that the influence of vari-

able disorder on transport and magnetotransport in Si-MOSFETs has been observed earlier. Both the temperature dependence $\rho(T)$ and magnetoresistance $\rho(B_\parallel)$ were found to be different in samples with different mobility [3,4] and in samples cooled down with different values of substrate bias voltage [25]. In these studies, however, the sample mobility was changed significantly. In contrast, in our studies we kept constant the sample mobility and all parameters relevant to electron-electron interaction.

To summarize, by cooling the same high-mobility Si-MOS sample from room temperature down to $T = 4$K at different fixed values of the gate voltage, we tested universality of the temperature and magnetic-field dependences of the resistivity near the 2D MIT. An important advantage of this approach is that the different cooldown procedures do not affect the parameters which control the contribution of the interaction effects to the resistivity. It has been found that in the vicinity of the transition ($\rho \sim h/e^2$), the sample-specific effects strongly affect $\rho(T)$; these effects vanish only when ρ decreases below $\sim 0.1h/e^2$ with increasing electron density. Non-universal behavior has been also observed for the magnetoresistance in parallel magnetic fields. The effect is especially dramatic in moderate ($E_F^* > g^*\mu_B B > T$) and strong ($g^*\mu_B B \gtrsim E_F^*$) fields: it extends to much higher electron densities (we observed pronounced non-universality of $R(B_\parallel)$ over a wide range $n = (1-3)\times 10^{11}\mathrm{cm}^{-2}$). Our results clearly demonstrate that the apparent metal-insulator transition in 2D involves both universal and sample-specific effects. These results also help to establish the borderline between the regimes where the electron transport in high-mobility Si MOS-structures is either universal or sample-specific. Understanding of the non-universal regime requires detailed knowledge of the interface disorder at low temperatures.

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